NASA Technical Paper 2362

September 1984

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NASA

NASA
Technical
Paper
2362

1984

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**Scientific and Technical
Information Branch**

Summary

The friction behavior of single-crystal silicon rubbed against the pure metals titanium, nickel, silver, and copper was studied. Experiments were conducted in room air under both dry and lubricated conditions. Reciprocating sliding of the metallic pin was done 30 times over the same path. The sliding direction of the pin specimen was parallel to $[11\bar{2}]$ on the (111) surface. The velocity was 1.4 mm/s, and the loads examined were from 25 to 200 g (0.25 to 2.0 N). Results of the experiments indicate that, for dry sliding, titanium and nickel, transition metals with a high chemical affinity for silicon, exhibited higher coefficients of friction than silver and copper, with a stick-slip motion being detected. On the wear track of the silicon surface rubbed against titanium cracks perpendicular to the rubbing direction were observed. These cracks resulted from the brittle character of silicon. This was observed only after dry sliding. Many transfer particles were detected on the silicon surface after both the dry and lubricated sliding. On the other hand, when silver and copper were rubbed on the silicon surface, the coefficient of friction was far lower because silver and copper have lower chemical affinities for silicon. With mineral oil lubrication the silicon behaved plastically.

Introduction

Semiconductors are materials for use in new, developing technologies. As is well known, the semiconductors (Si, Ge, etc.) are the fundamental materials of the electronic and electrical industries. Current tribological studies on semiconductors have been developing. The problems associated with metal-semiconductor contacts were very actively investigated in recently developed electric devices (refs. 1 and 2). The abrasive nature of semiconductors (silicon) has been studied in reference to surface finishing of semiconductors (refs. 3 and 4). Basic information concerning the tribological properties of semiconductors, however, is not adequate. Only a few experiments on the friction, adhesion, and wear of silicon and germanium in contact with metals have been performed. In high-vacuum experiments with silicon and germanium in contact with single-crystal gold and iron (ref. 5), the effects of the orientation and doping on friction and adhesion were studied. The influence of the environment on the friction of iron for iron rubbing against silicon (111) and germanium (111) surfaces was also investigated (ref. 5). Friction studies on group IV elements ion-plated onto a single-crystal nickel (011) surface in contact with single-crystal gold (111) indicated that the covalent germanium film had lower adhesion than the metallic tin film. The silicon film had low friction, and it was more affected by the presence of oxygen than lead (ref. 6). Wear experiments of phosphorus-doped single-crystal silicon (100) rubbed against polycrystalline aluminum, zinc, copper, iron, nickel, and molybdenium indicated low wear rates (10^{-8} to 10^{-9} mm^3/mm•kg) under dry conditions (ref. 7).

In the present investigation friction behavior was studied for a single-crystal silicon (111) surface mating with polycrystalline titanium, nickel, silver, and copper. The differences in the friction behavior of silicon were ascribed to differences in the properties of the contacting metals (transition or the nontransition metals). In the experiments the load was 25 to 200 g (0.25 to 2.0 N); the sliding velocity was 1.4 mm/s. The experiments were conducted under two conditions, dry and with mineral oil lubrication, in room air (30 to 35 percent relative humidity) at room temperature (21° C). The metallic pin specimens moved in reciprocating sliding 30 cycles (60 passes) on the same path in the parallel $[11\bar{2}]$ direction on the silicon (111) surface. The wear tracks on the silicon surfaces were subsequently examined with the scanning electron microscope.

Materials

The metals used as pin specimens were two transition metals, titanium and nickel, and two nontransition metals, silver and copper. All were pure polycrystalline metals (table I). The diameter of each metallic pin was 3.18 mm, and the sliding surface was a hemispherical shape with a radius of 1.59 mm. The sliding surface was polished with 0.3-μm alumina powder. The specimens were cleaned with water after polishing and then were degreased with ethyl alcohol in an ultrasonic cleaner.

The silicon was a single-crystal plate of (111) orientation and was 500 μm thick. The polished silicon surface (roughness, R_{max}, ~0.01 μm) was degreased with ethyl alcohol before experiments in the same way as the metal specimens. The sliding direction of the pin specimen on

TABLE I.—PURITY OF PIN SPECIMEN

Metal	Purity, percent
Titanium	99.97
Nickel	99.995
Silver	99.999
Copper	99.999

the silicon (111) surface was set in parallel to the [11$\bar{2}$] crystal direction. The lubricant was mineral oil, and no treatment was given the oil before experiments.

Apparatus

The apparatus used for the experiments was a pin-plate type device (fig. 1). The pin specimen was mounted on a gimbal. On the beam were two machined flats, normal to each other, on which strain gages were mounted. Friction force was measured by the strain gage mounted on the flat nearer to the pin specimen. Load was applied to the pin specimen holder with weights of 25 to 200 g (equivalent to 0.25 to 2.0 N).

The single-crystal silicon plate was mounted on a 25.4-mm square platform. The platform was mounted on a stage which was moved in reciprocating motion by a revolving screw and gear linkage. The stroke of the reciprocating motion of the stage was 10 mm, and the movement direction was reversed from one direction to another by relay switches. The sliding speed was 1.4 mm/s in both directions. In each experiment the pin specimen rubbed the same 10-mm path of the silicon (111) surface 60 times, that is, 30 times in each direction.

The experiments were conducted dry and under mineral-oil-lubricated conditions in room air (30 to 35 percent relative humidity) and room temperature (21° C). In the lubricated (boundary lubricating) case, mineral oil was dropped onto the silicon plate surface at a rate of 0.03 cc per reciprocating cycle.

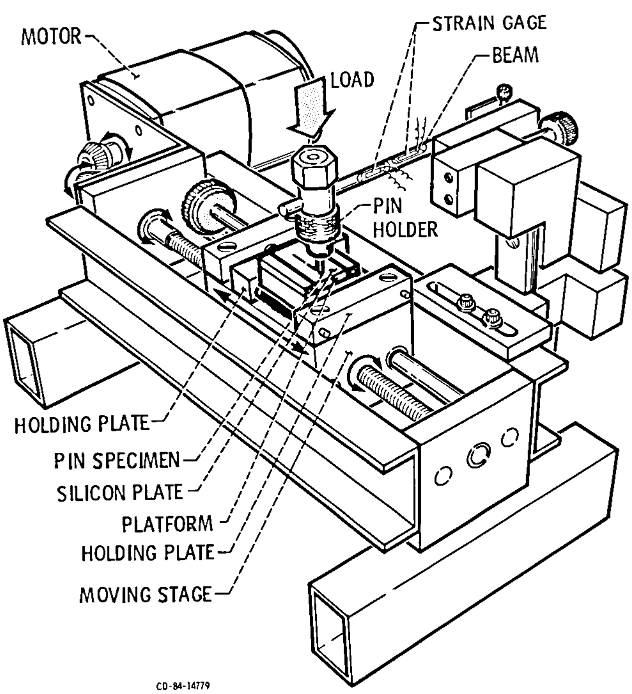

Figure 1.—Friction apparatus.

Results and Discussion

The coefficients of friction as a function of load for the dry sliding of single-crystal silicon (111) against titanium, nickel, silver, and copper are presented in figure 2. The coefficients of friction for the transition metals titanium and nickel were larger than those of the nontransition metals silver and copper. The coefficient of friction for the titanium-silicon rubbing combination was 0.50 to 0.67, with the higher values representing the smaller load. For the nickel-silicon combination the coefficient of friction was 0.36 to 0.48, which is smaller than the titanium-silicon combination but which shows the same trend. A stick-slip motion was found with these two couples, and the friction force changed with the number of passes on the same path (figs. 4 and 6). The coefficients of friction for these couples was calculated from the maximum friction force after the steady-state processes was achieved.

In the sliding of silver on the silicon, on the other hand, the coefficient of friction was 0.2, and it was not affected by increasing the load. The coefficient of friction of copper rubbed against silicon was nearly the same as with the silver, but varied little with load. The value of 0.2 measured is remarkably low for the friction of materials in dry sliding conditions; for example, the coefficient of dry friction of metal on metal in air is usually 0.4 to 1.2.

Figure 3 indicates the coefficient of friction for the four metals sliding on silicon with mineral oil lubrication.

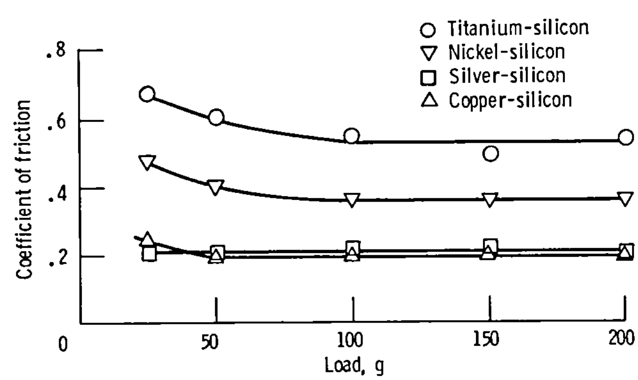

Figure 2.—Coefficient of friction in dry sliding. Sliding speed, 1.4 mm/s.

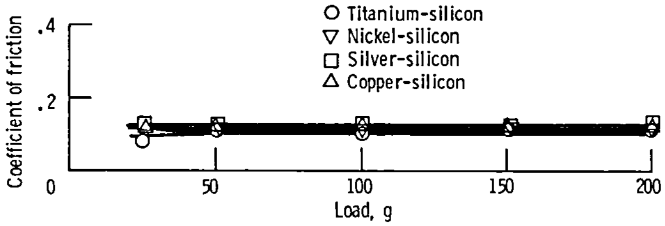

Figure 3.—Coefficient of friction in lubricated sliding. Sliding speed, 1.4 m/s; lubricant, mineral oil.

The coefficients of friction were 0.08 to 0.14, and any differences among four pin metals was not significant. The variation of coefficient of friction with load for the titanium-silicon and nickel-silicon couples found in the dry state (fig. 2) disappeared under lubricated conditions, and the reduction effects of lubrication on the friction of the titanium-silicon system was larger than for these couples of the others.

The following observations can be made about the friction behaviors of the titanium-silicon and silver-silicon pairs. The behaviors of nickel and copper sliding on the silicon were the same as those of titanium and silver, respectively.

Figure 4 shows the variation of friction force for titanium rubbed on the silicon surface in one sliding pass 10 mm (a half cycle of the reciprocating motion) for dry and lubricated conditions at a load of 25 g. The stick-slip motion is clearly found only in dry sliding.

The variation of friction force for the silver-silicon system is presented in figure 5. The stick-slip motion is absent in both dry and lubricated sliding conditions.

Figure 6 shows the variation of friction with repeated cycles of sliding on the same path of silicon with titanium and silver. The existence of surface films, such as chemisorbed gas films or oxide films, is extremely important to friction behavior. This is especially true for transition metals, such as titanium, which have a high chemisorption activity for environmental gas molecules (ref. 8). This high activity is related to the empty d-electron orbitals for these metals. The friction of titanium rubbed against silicon was low in the initial stage of sliding and then gradually increased with repeated sliding on the same path. After six or more passes the metal-silicon contact increased, and the coefficient of friction increased. The frictions for titanium and nickel are higher than those for silver and copper after breaking through the surface films (fig. 2). The reason is that titanium and nickel make strong adhesive bonds to the silicon surface because these transition metals are very interactive with silicon (refs. 2 and 9). Since silver and copper, nontransition metals, do not have strong chemisorbed gas films on their surfaces and do not have the strong activity with silicon, the coefficients of friction were low for these metals rubbing against silicon. Further, they did not change with repeated passes of sliding.

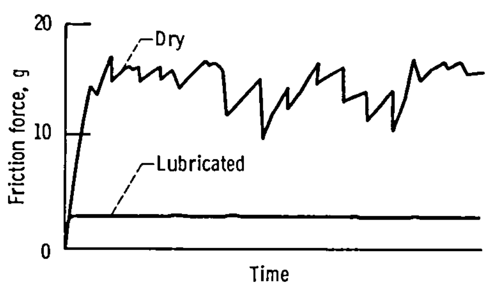

Figure 4.—Friction force of titanium-silicon couple versus friction time. One rubbing stroke (10 mm); sliding speed, 1.4 mm/s; load, 25 g.

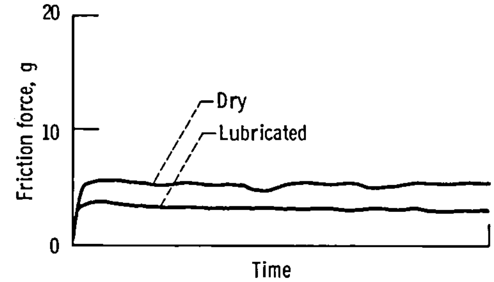

Figure 5.—Friction force of silver-silicon couple versus friction time. One rubbing stroke (10 mm); sliding speed, 1.4 mm/s; load, 25 g.

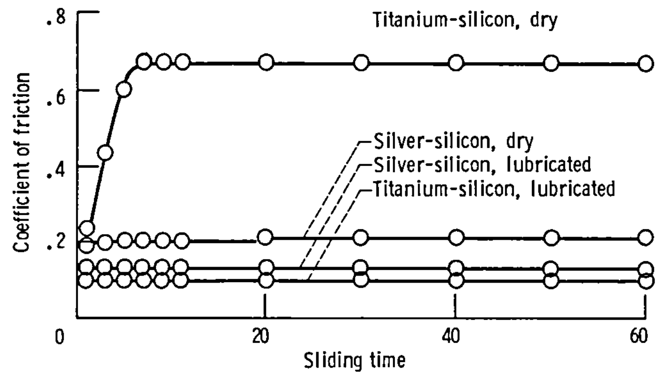

Figure 6.—Variation of coefficient of friction with sliding time. Sliding speed, 1.4 mm/s; load, 25 g; lubricant, mineral oil.

Figure 7 is a scanning electron micrograph of the silicon (111) surface rubbed against titanium in the dry condition at a load of 25 g (0.25 N). The observation was made in the wear track after the metallic pin had rubbed the full 30 cycles on the same track. On the wear track cracks were found perpendicular to the sliding direction, that is, parallel to the $[1\bar{1}0]$ direction on the (111) surface. Many particles were observed along the sliding path. They were comparatively large (about 10 μm). The particles were identified as silicon particles by energy dispersive X-ray analysis. Surface damage was the generation of cracks in the brittle solid, silicon.

The mineral-oil lubricated silicon surface rubbed against titanium is presented in figure 8 at the same load and sliding velocity as figure 7. No cracks like those of

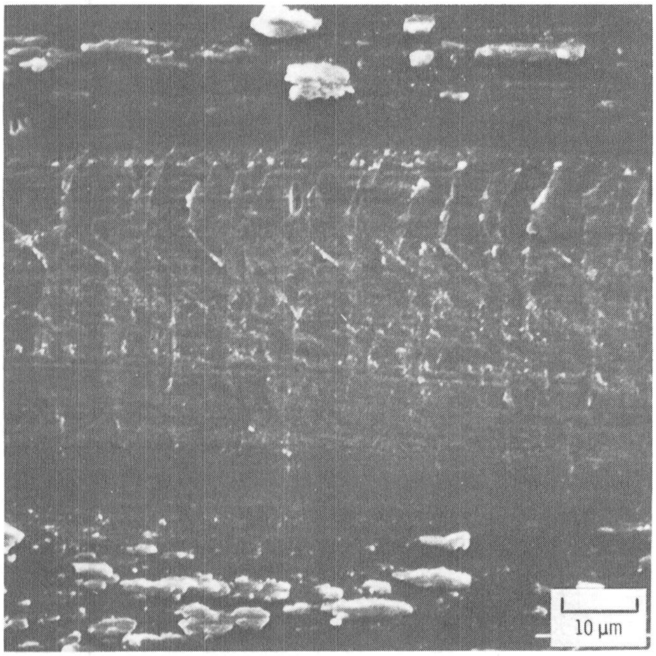

Figure 7.—Wear track of a silicon (111) surface rubbed against titanium dry. (The sliding direction is horizontal.)

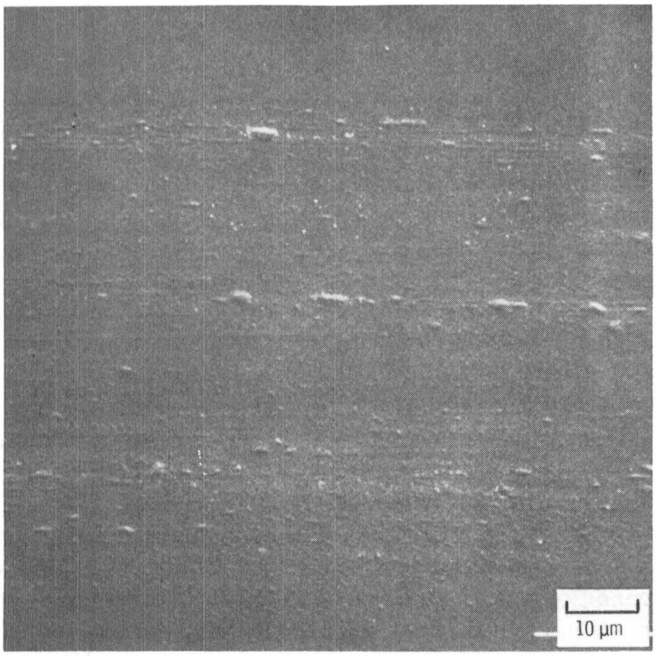

Figure 8.—Wear track of silicon (111) surface rubbed against titanium with mineral oil lubrication. (The sliding direction is horizontal.)

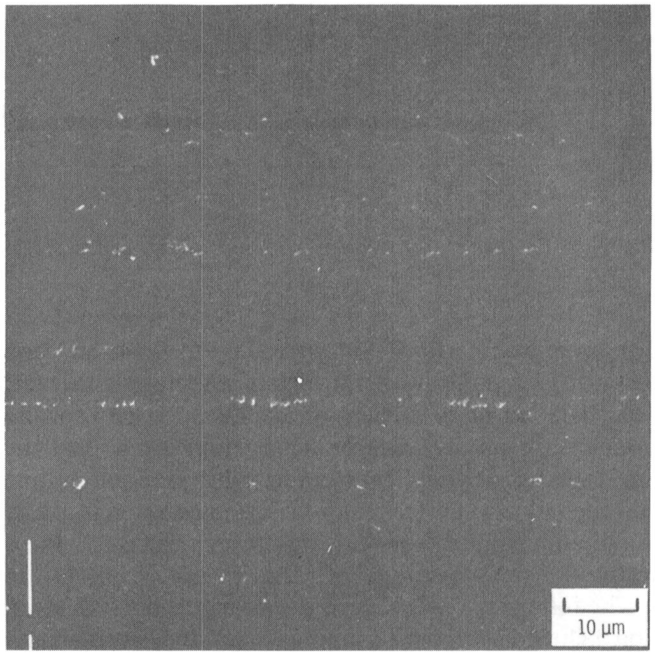

Figure 9.—Wear track of a silicon (111) surface rubbed against silver dry. (The sliding direction is horizontal.)

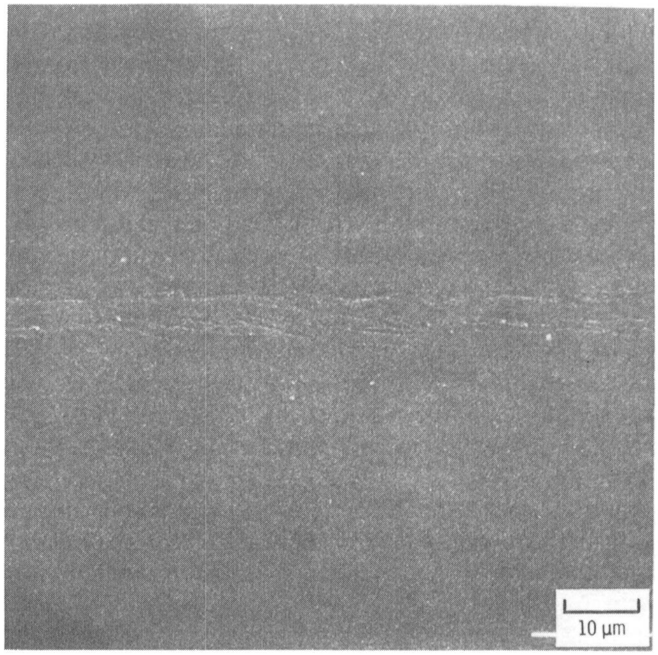

Figure 10.—Wear track of silicon (111) surface rubbed against silver with mineral oil lubrication. (The sliding direction is horizontal.)

figure 7 were found in the wear track; however, many particles of a few micrometers or less in size are found on the sliding surface.

The surface of silicon rubbed with silver can be seen in the micrographs of figure 9 (dry) and figure 10 (lubricated). In dry sliding, although many transfer particles are found in the sliding track, no cracks are observed. In lubricated sliding the rubbing track was grooved, and the silicon behaved plastically.

As indicted in figures 7 to 10 the silicon surfaces are much different in appearance, depending on not only the sliding conditions but the sliding metals as well. The cracking fracture on the track could be generated in dry sliding with titanium. In this case the silicon appeared to

be brittle in character. However, this character did not appear when silicon was rubbed with silver, which had a weak chemical affinity for silicon. Under lubricated conditions, silicon behaved plastically. This observation has already been indicated in previous work (ref. 5). In the present experiments the brittle character of silicon appeared when strong adhesion occurred and when a high friction force existed between silicon and titanium or nickel, both of which have a strong chemical affinity for silicon.

Conclusions

The friction behavior of single-crystal silicon rubbing against polycrystalline titanium, nickel, silver, and copper were studied in dry sliding and with mineral-oil lubrication. From the measurements of the coefficient of friction and the observations of the tracks, the following points are made:

1. The coefficients of friction for silicon rubbed against titanium and nickel were higher than those for silicon rubbed against silver and copper in dry sliding. The coefficient is directly related to the chemical activity of the metal: the more active the metal the higher the friction.
2. Stick-slip motion was found only when silicon was rubbed against titanium and nickel in the dry state. In the friction of silicon sliding against silver or copper, stick-slip motion could not be found either in dry or lubricated sliding conditions. Stick-slip behavior relates to adhesion and, accordingly, the chemical activity of the metal.
3. With mineral-oil lubrication there was no difference in the coefficients of friction among the four metals, indicating that the presence of the oil completely masks metal chemical effects.
4. Many transfer particles were found in the wear tracks of silicon rubbed against both titanium and silver, although few were found after rubbing silver under lubricated conditions.
5. The silicon appeared brittle when rubbed against titanium in the dry state. A high coefficient of friction is consistent with the strong chemical activity of titanium for silicon. This type of behavior was not found in the rubbing of the weakly active nontransition metal, silver. The silicon in contact with silver behaved plastically under lubricated conditions. These results indicate the importance of surface chemistry. When metals can adhere strongly to the silicon (dry sliding), the silicon behaves in brittle manner. When, however, a lubricant is present and it prevents metal to silicon adhesion, the silicon deforms plastically under load.

Lewis Research Center
National Aeronautics and Space Administration
Cleveland, Ohio, June 4, 1984

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1. Report No.
NASA TP-2362

2. Government Accession No.

3. Recipient's Catalog No.

4. Title and Subtitle

Friction Behavior of Silicon in Contact With Titanium, Nickel, Silver, and Copper

5. Report Date

September 1984

6. Performing Organization Code

506-53-1B

7. Author(s)

Hiroshi Mishina and Donald H. Buckley

8. Performing Organization Report No.

E-2036

10. Work Unit No.

9. Performing Organization Name and Address

National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135

11. Contract or Grant No.

13. Type of Report and Period Covered

Technical Paper

12. Sponsoring Agency Name and Address

National Aeronautics and Space Administration
Washington, D.C. 20546

14. Sponsoring Agency Code

15. Supplementary Notes

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16. Abstract

Sliding friction experiments were conducted with the semiconductor silicon in contact with the metals titanium, nickel, copper, and silver. Sliding was on the (111) plane of single-crystal silicon in the $[11\bar{2}]$ crystallographic direction both in dry and lubricated (mineral oil) sliding. Results indicate that the friction coefficient in dry sliding is controlled by adhesion and, accordingly, the surface chemical activity of the metal. The more active the metal the stronger the adhesion and the higher the friction. In lubricated sliding the lubricant absorbs to the surfaces and reduces the importance of metal chemical effects. In lubricated sliding silicon ceases to behave in a brittle manner and undergoes plastic deformation under load.

17. Key Words (Suggested by Author(s))

Friction; Semiconductor; Boundary lubrication, Metal-silicon contact

18. Distribution Statement

Unclassified - Unlimited
STAR Category 27

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of pages	22. Price*
Unclassified	Unclassified	7	A02

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